

# WISE 2014 @

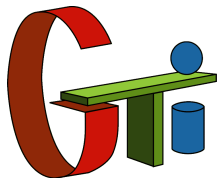


## Space-time ocean wave measurement using variational stereo vision systems

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June 12, 2014



**Georgia Institute  
of Technology**

# Outline

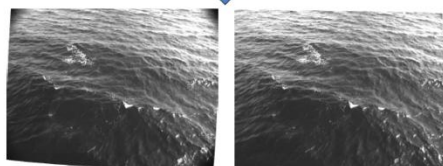
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- Some vision-based systems for wave measurement
- Two variational stereo methods: disparity, elevation.
- Extensions
  - Enforce wave height models
  - Space-time processing
  - Refinement of camera parameters
- Conclusions

# What? and Why?

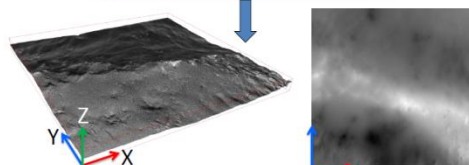


Vision acquisition system at offshore platforms:  
Adriatic and Black Seas



Multi-view videos

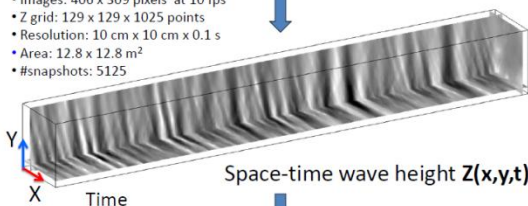
Variational stereo,  
Multigrid methods



Estimated wave height (Z), surface model

Temporal processing

- Images: 406 x 309 pixels at 10 fps
- Z grid: 129 x 129 x 1025 points
- Resolution: 10 cm x 10 cm x 0.1 s
- Area: 12.8 x 12.8 m<sup>2</sup>
- #snapshots: 5125



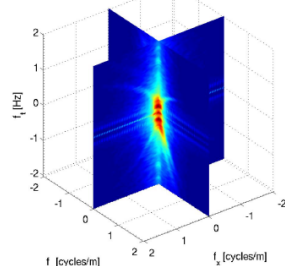
Space-time wave height  $Z(x,y,t)$

Data Analysis

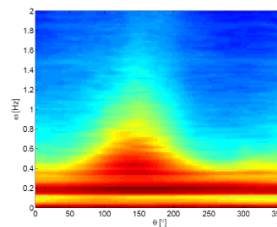
## 2. Data Analysis

### Spectra

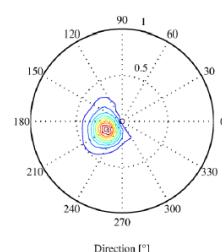
Distribution of energy in frequency domain.



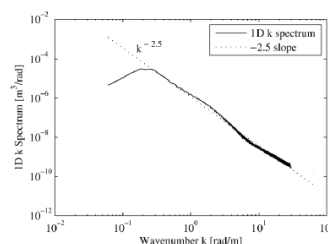
Estimated 3D power spectrum.



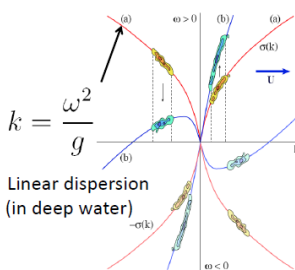
Directional spectrum  $F(\omega, \theta)$



Directional spectrum.



Omni-directional spectrum.  
in wavenumber  $k$  (rad/m)



Linear dispersion  
(in deep water)

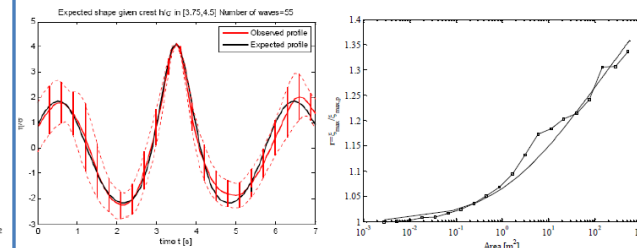
Estimate surface currents causing Doppler shift of dispersion.

### Statistics

Analysis of time series at virtual probes.

		$H_{m0}$ [m]	$H_{1/3}$ [m]	$H_{max}$ [m]	$T_p$ [s]	$T_z$ [s]	$Dir$ [° N]
Exp 1	CNR	—	0.47	0.68	—	2.91	—
	WASS	0.45	0.41	0.83	4.34	3.09	$148.5 \pm 3$
Exp 2	CNR	1.13	1.09	2.03	4.59	3.51	$65.0 \pm 3$
	WASS	1.15	1.10	2.18	4.83	3.62	$59.5 \pm 3$
Exp 3	CNR	2.23	2.16	3.80	6.37	4.62	$69.7 \pm 3$
	WASS	2.17	2.16	3.95	6.36	4.85	$70.1 \pm 3$

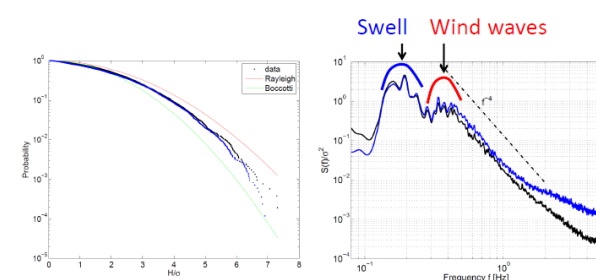
Wave parameters estimated from both WASS instruments operational at *Acqua Alta*.  $Dir$  is the mean wave direction of propagation, measured clockwise from geographic North (wave directions depend upon the platform orientation that is known with an error  $\sim 3^\circ$ ). During Experiment 1,  $H_{m0}$ ,  $H_{1/3}$ , and  $Dir$  were not available at *Acqua Alta*.



Space-Time Extremes of Oceanic Seas.

Expected shape of largest waves.

Ratio between the expected maximum wave height over an area and that expected at a point.



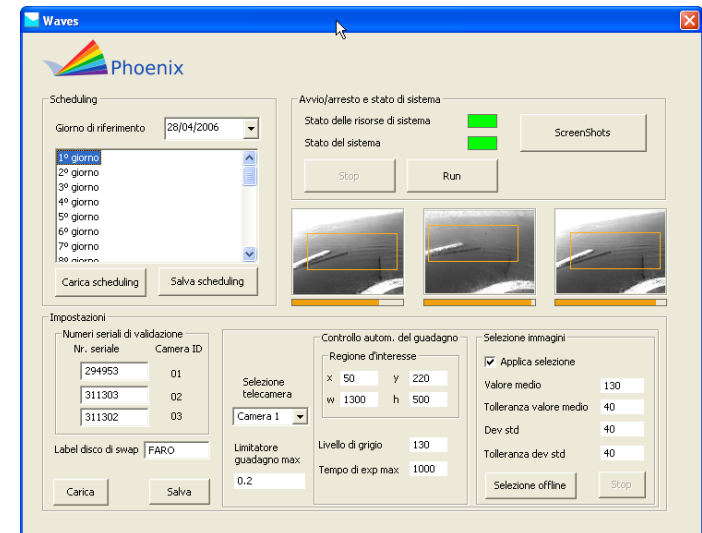
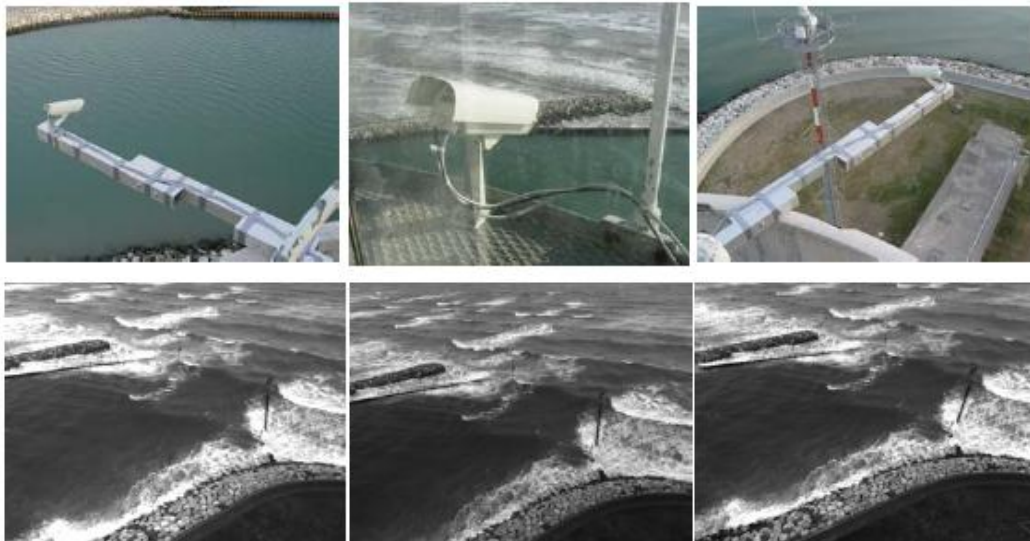
Wave height exceedance prob.

Normalized freq. Spectrum  
(disparity, elevation methods)

# Literature review. WASS (Benetazzo, 2006)

Goal: to study and predict ocean wave patterns from image sensors

- Image acquisition  
(Bi/Trinocular synchronized and calibrated digital cameras)

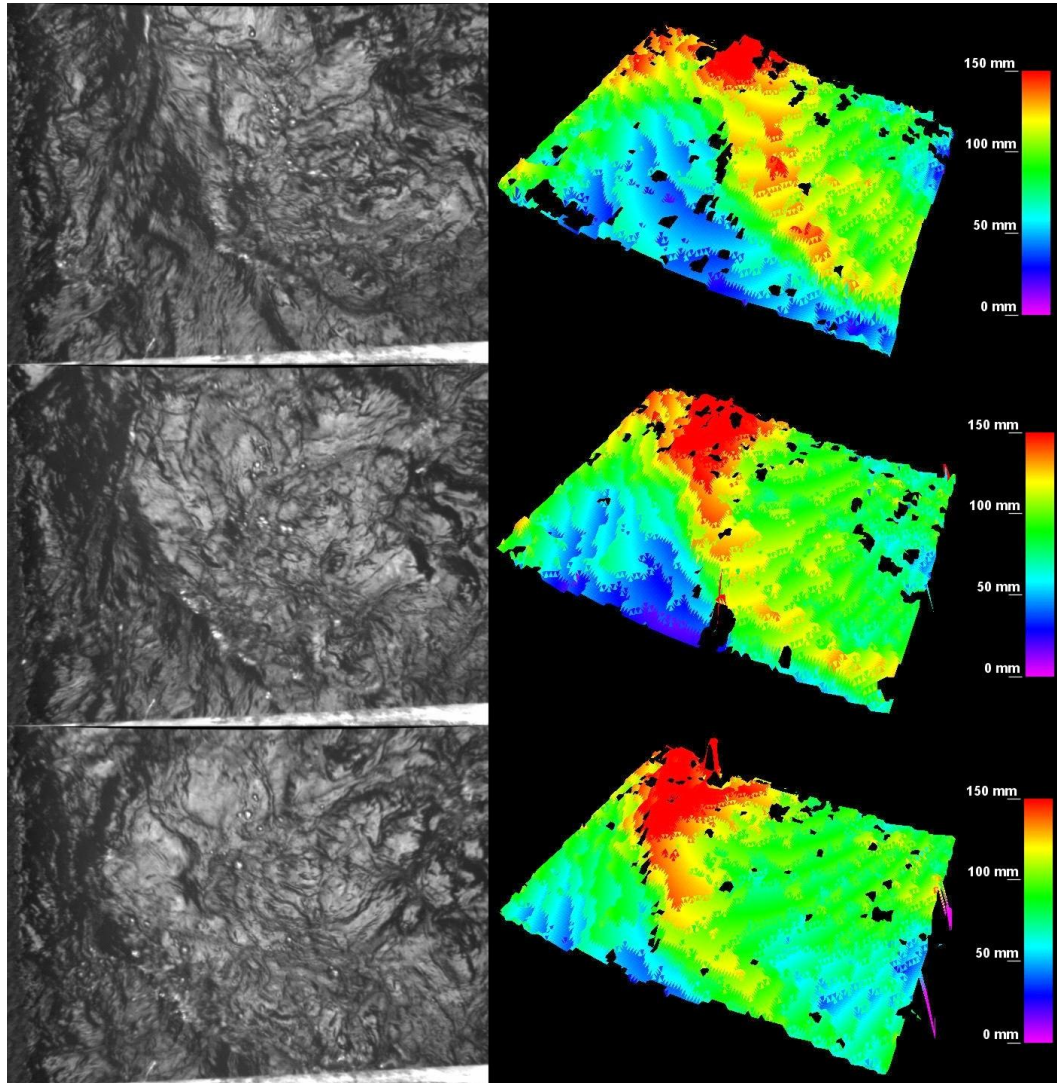


- Image processing  
Reconstruct the surface of the water (epipolar stereo method)



# Literature review. WASS (Benetazzo, 2006)

Water surface elevation in *time*:  
from 2D image sequences to 3D map sequences



- $Z_0 \sim 1.70$  m,  $b = 0.22$  m
- Matched Area :  $0.94 \times 0.78$  m<sup>2</sup>
- $e_{rx} = e_{ry} = 0.15$  cm,  $e_{rz} = 0.69$  cm
- 90 % of points matched
- 480 x 640 pixel camera
- $F = 6.3$  mm,  $ss = 1/200$  s

# Literature review. ATSIS

- Automatic Trinocular Stereo Imaging System (ATSIS)  
(Wanek and Wu, 2006).
- Measurement and analysis of ocean wave fields in 4D  
(MacHutchon and Liu, 2007, 2009).
- Virtual wave gauges for measuring surface wave characteristics  
(Bechle and Wu, 2011).

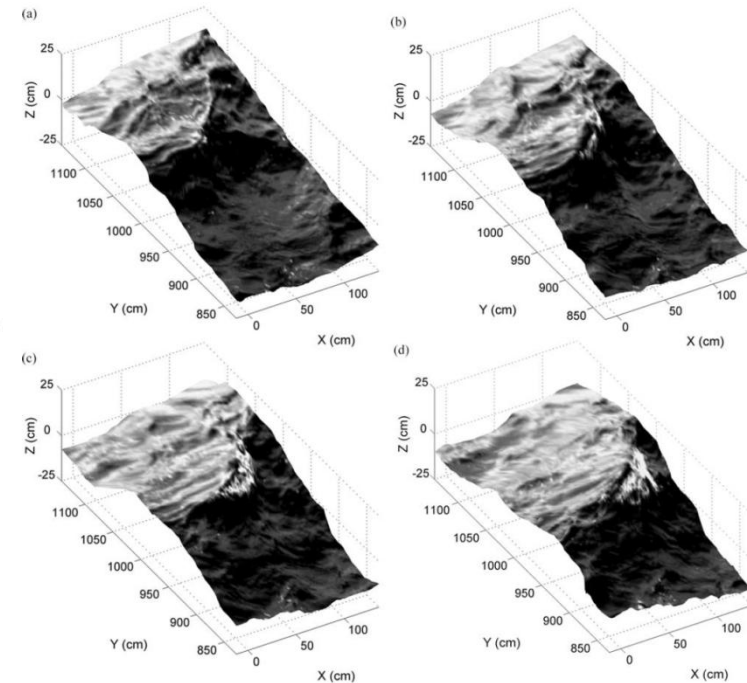
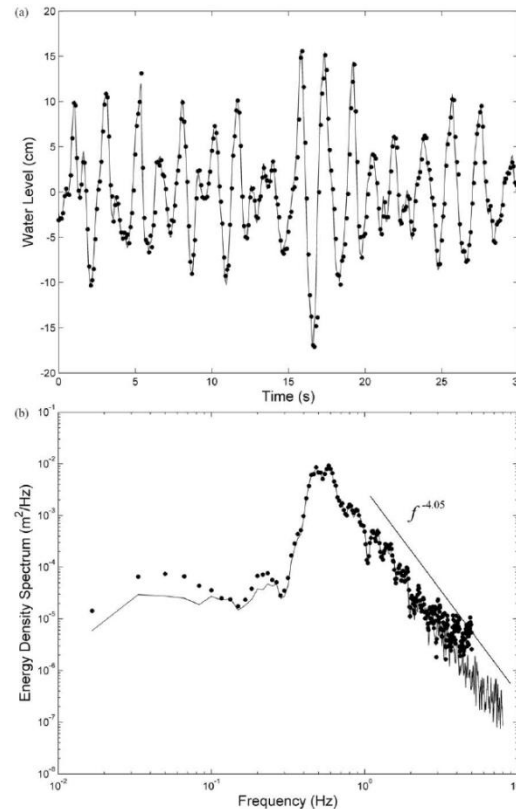
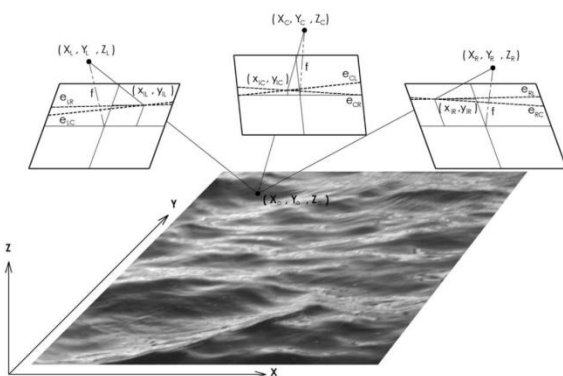
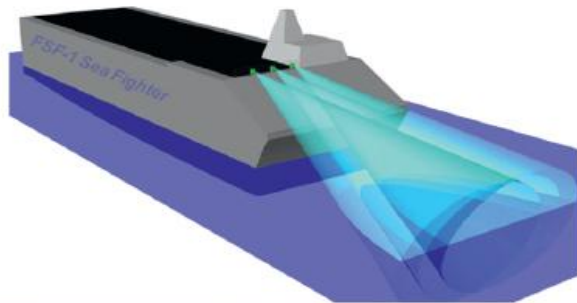


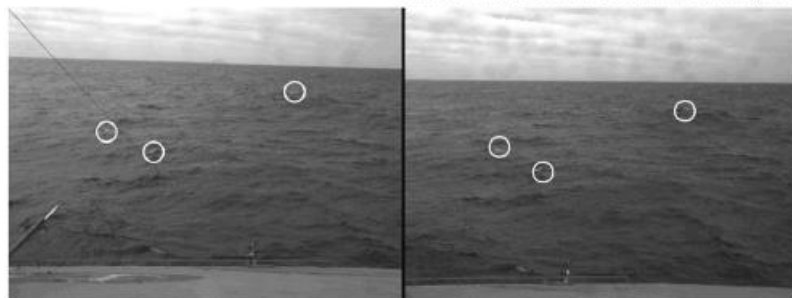
Fig. 9. A temporal evolution of a three dimensional wave breaking event at (a)  $t=0.0$  s, (b)  $t=0.1$  s, (c)  $t=0.2$  s, (d)  $t=0.3$  s, (e)  $t=0.4$  s, and (f)  $t=0.5$  s.

# Literature review. Stereo systems

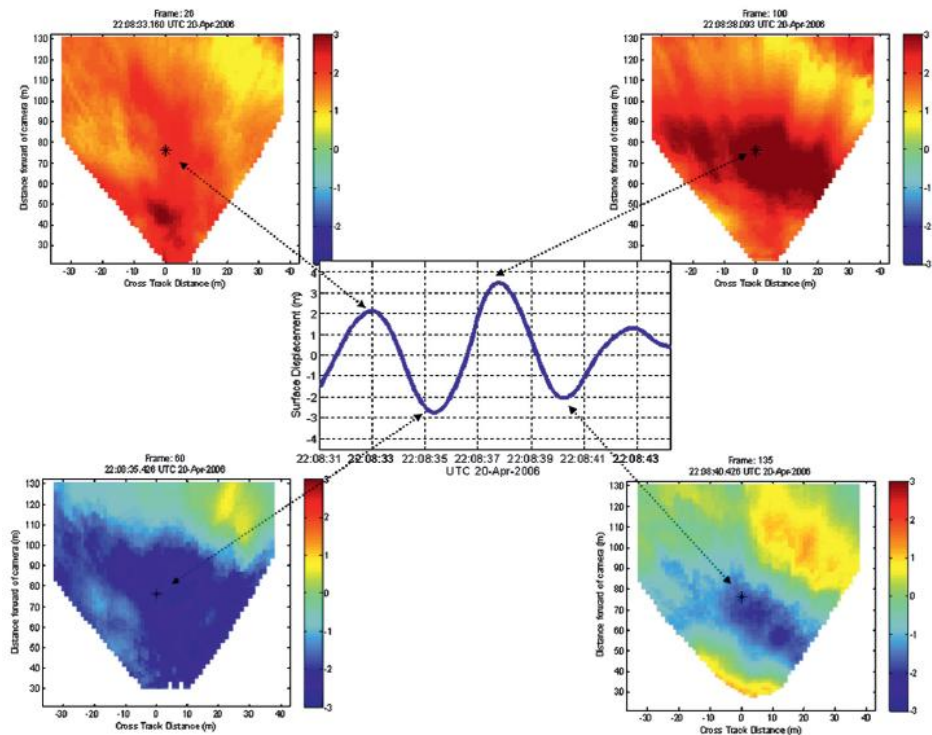
- Three-Dimensional Imaging of the High Sea-State Wave Field encompassing ship slamming events (Brandt et al 2010).



22:08:36 UTC 20 Apr 2006 Run 153 Starboard Quartering Seas



Middle Camera 2.4 m separation Starboard Camera





# Literature review. Stereo systems

- Remote sensing of surf zone waves using stereo imaging  
(S. de Vries et al, 2011)

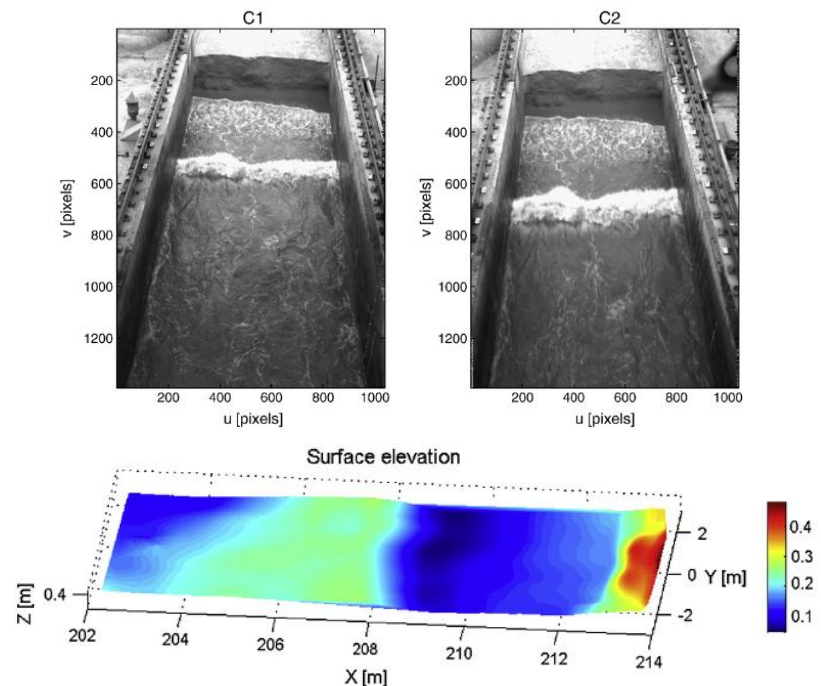


Fig. 12. Perspective view of the sample reconstruction of water surface elevation. Color contours denote elevation in meters.

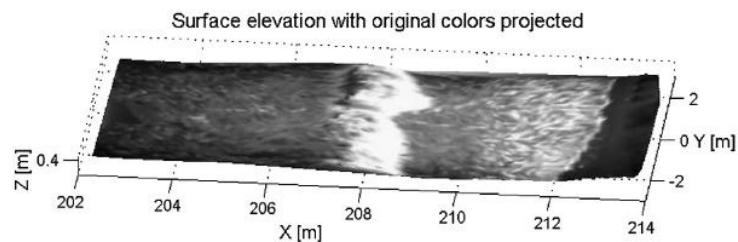
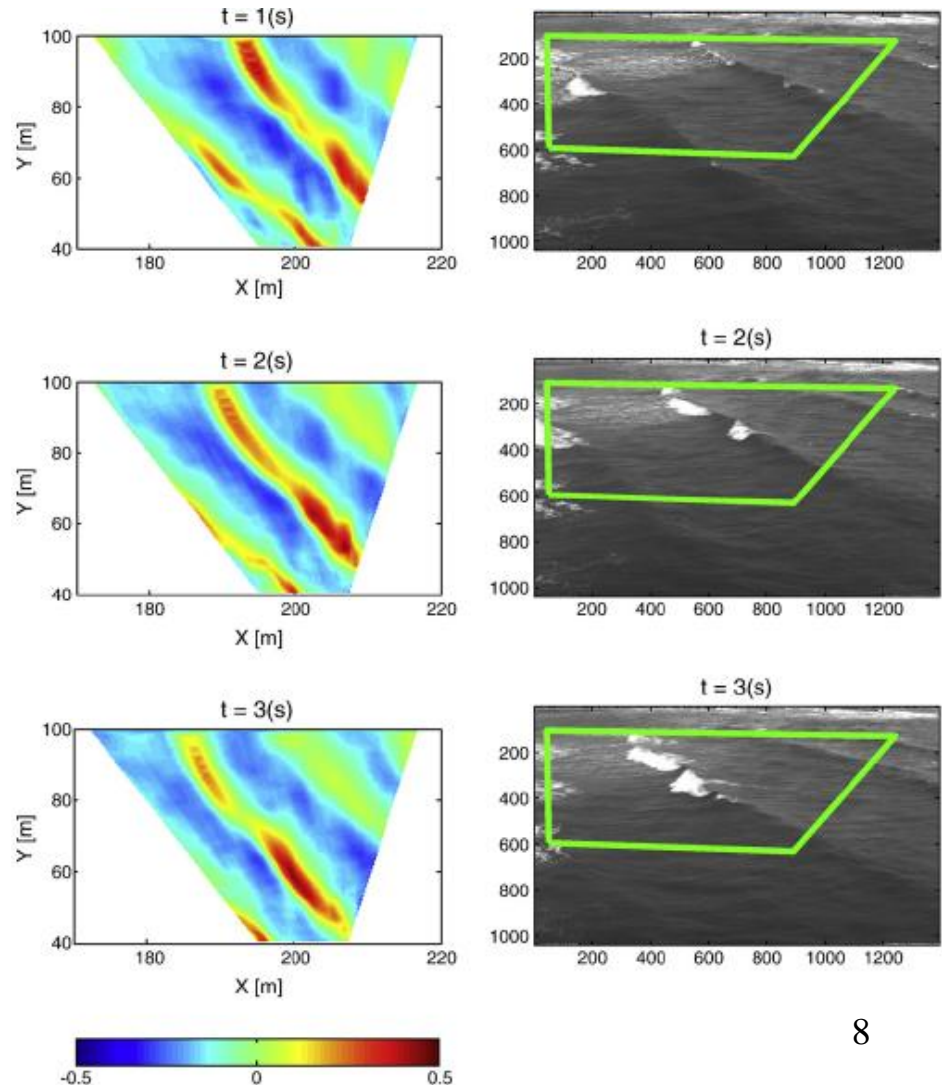


Fig. 13. Perspective view of original camera image mapped onto the three-dimensional water surface elevation.



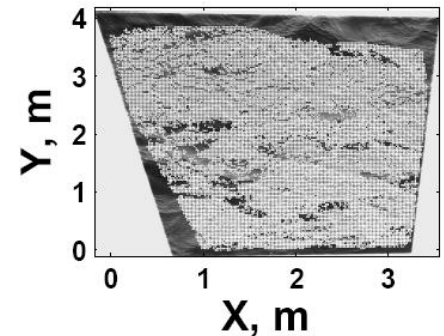
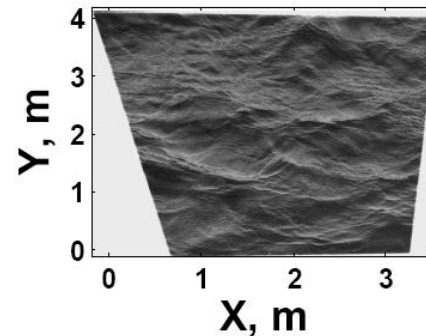


# Literature review. Stereo systems

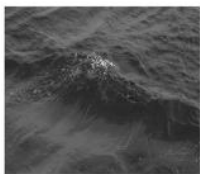
- Extraction of short wind wave spectra from stereo images (Kosnic and Dulov, 2011).
- Statistical characterization of short wind waves (Mironov, Kosnik, Dulov, Hauser, Guérin, 2012).



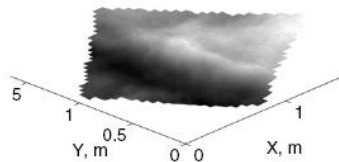
Problem: gaps (holes) in reconstructed surface



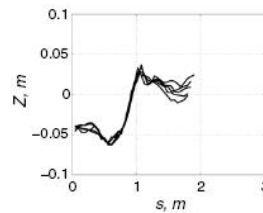
Sample reconstructions:



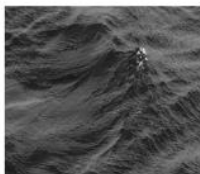
(d)



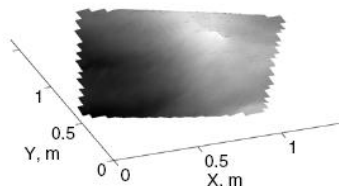
(e)



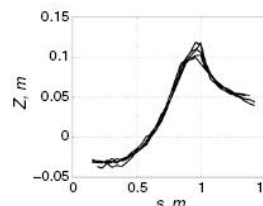
(f)



(g)

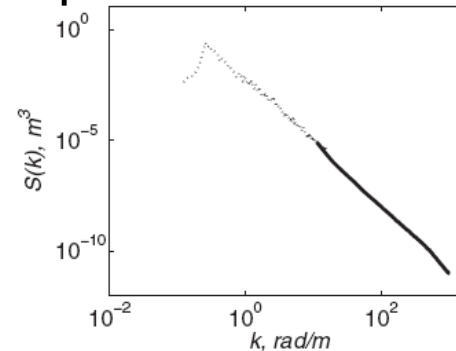


(h)



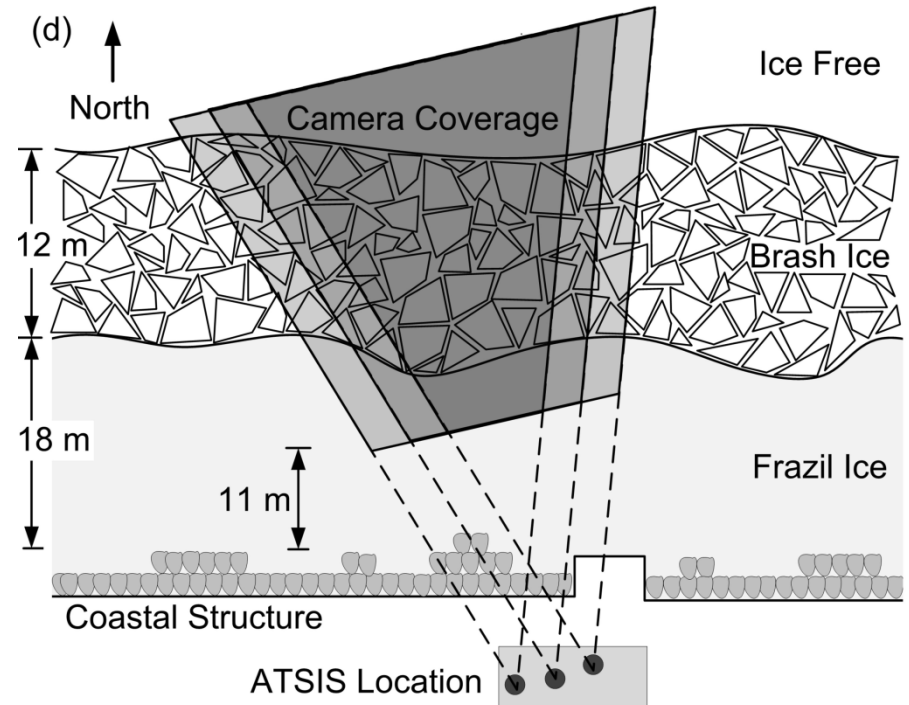
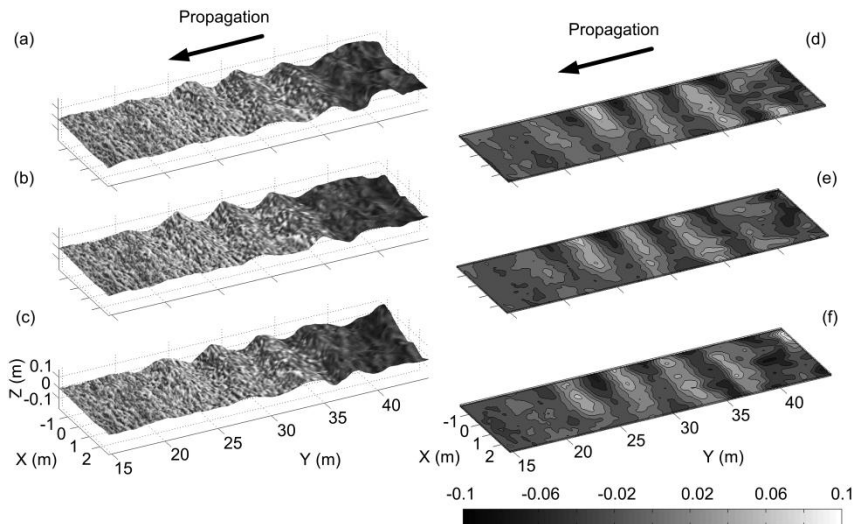
(i)

Spectrum



# Literature review. ATSIS

- Observations of Surface Waves Interacting with Ice using Stereo Imaging (Campbell, Bechle, Wu, 2014).



# Classical stereo methods

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Difficulties / disadvantages:

- Point correspondences are not easy to find.
- Very sensitive to image noise.
- Unmatched regions: gaps in the surface.
- Requires strongly textured surfaces.
- Each point is treated independently (does not exploit continuity of surface).
- Considerable post-processing is required.

How do we work around it?

# Advantages of variational methods

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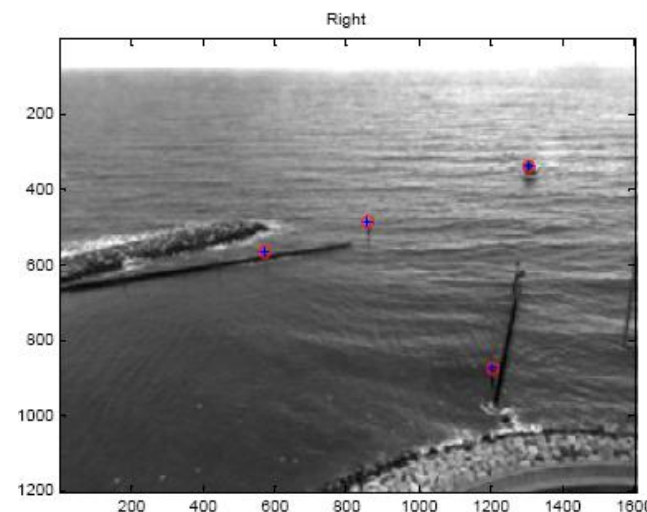
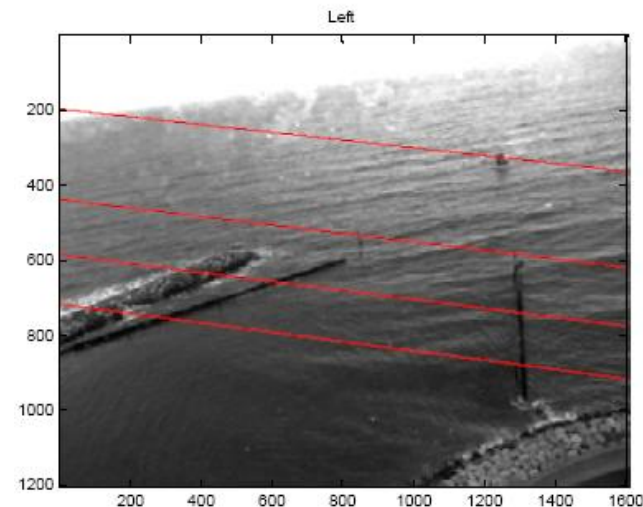
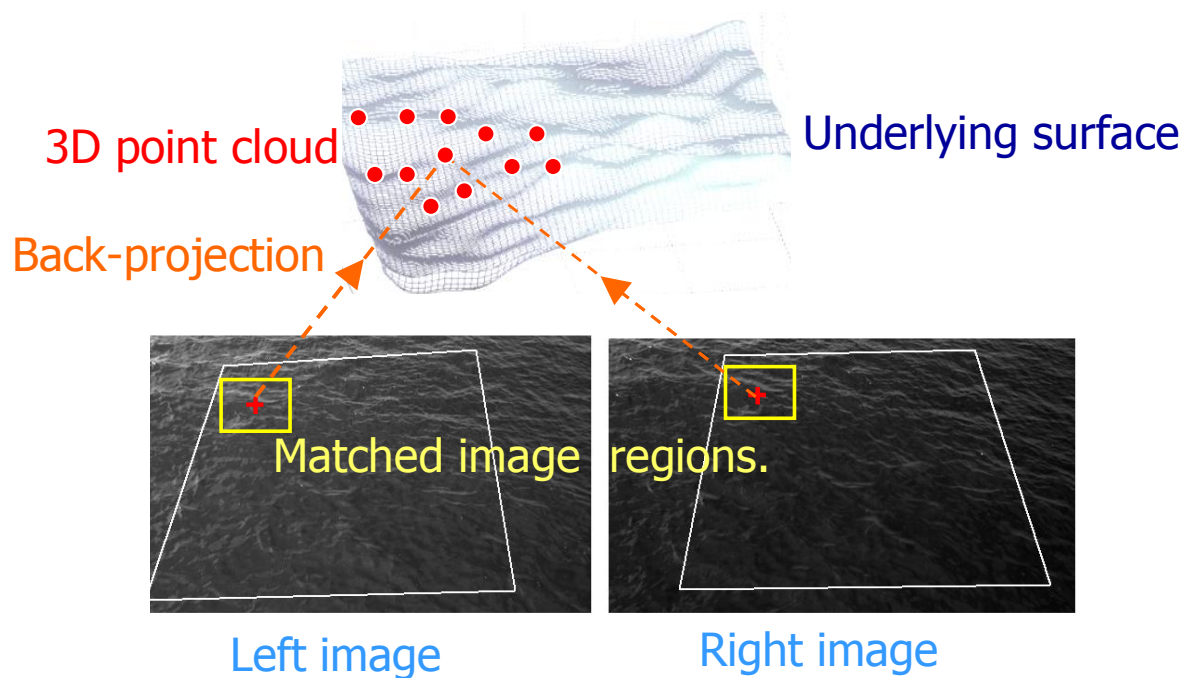
- Enforce continuity of the wave surface in space & time:  
recovered points are not treated independently.
- Improve robustness: less sensitive to matching problems.
- Provide dense surface reconstructions.
- Allow controllability/priors on the unknowns.
- Can incorporate global properties of wave heights.
- Imply less post-processing than classical methods.



# Dense disparity map method (1 snapshot)

Steps:

1. Compute matching between images (dense disparity)
2. Back-project matched points to 3-D world
3. Fit a surface through the points



# Dense disparity map method

Variational optimization approach to point matching:

- Cost functional:  $E = E'_{\text{data}} + \alpha' E_{\text{smooth}}$  , with

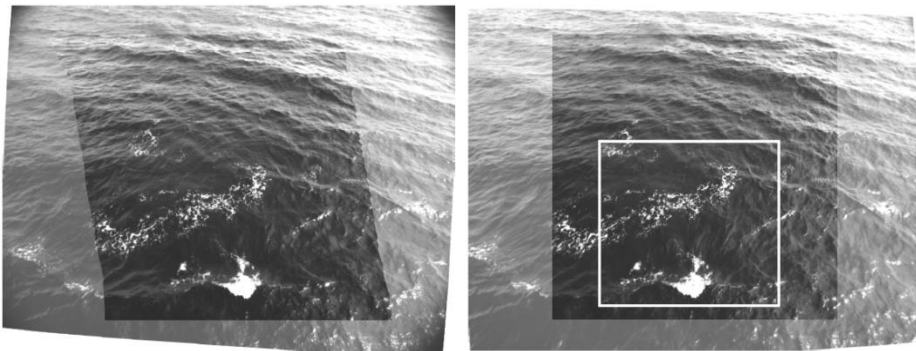
$$E'_{\text{data}}(\lambda) = \int_{\Omega} \frac{1}{2} (I_1(\mathbf{x}_1) - I_2(\mathbf{x}_2))^2 d\mathbf{x}_1$$

$$E_{\text{smooth}}(\lambda) = \int_{\Omega} \frac{1}{2} \|\nabla \lambda\|^2 d\mathbf{x}_1$$

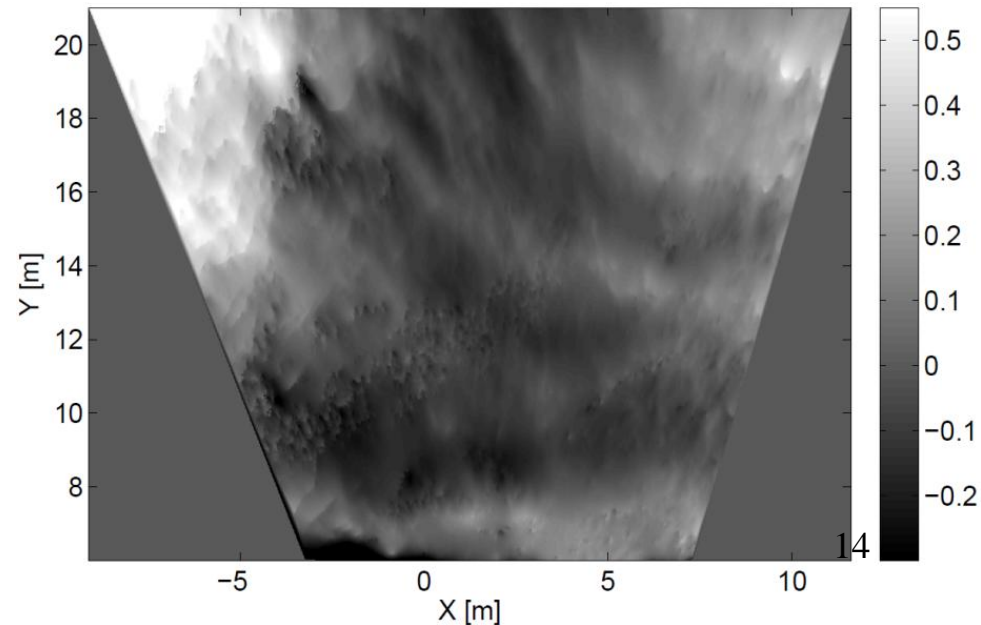
- Unknown: 2-D coherent disparity map.

## Euler-Lagrange equations

$$\alpha' \Delta \lambda + (I_1(\mathbf{x}_1) - I_2(\mathbf{x}_2)) \frac{\partial I_2(\mathbf{x}_2)}{\partial \lambda} = 0$$

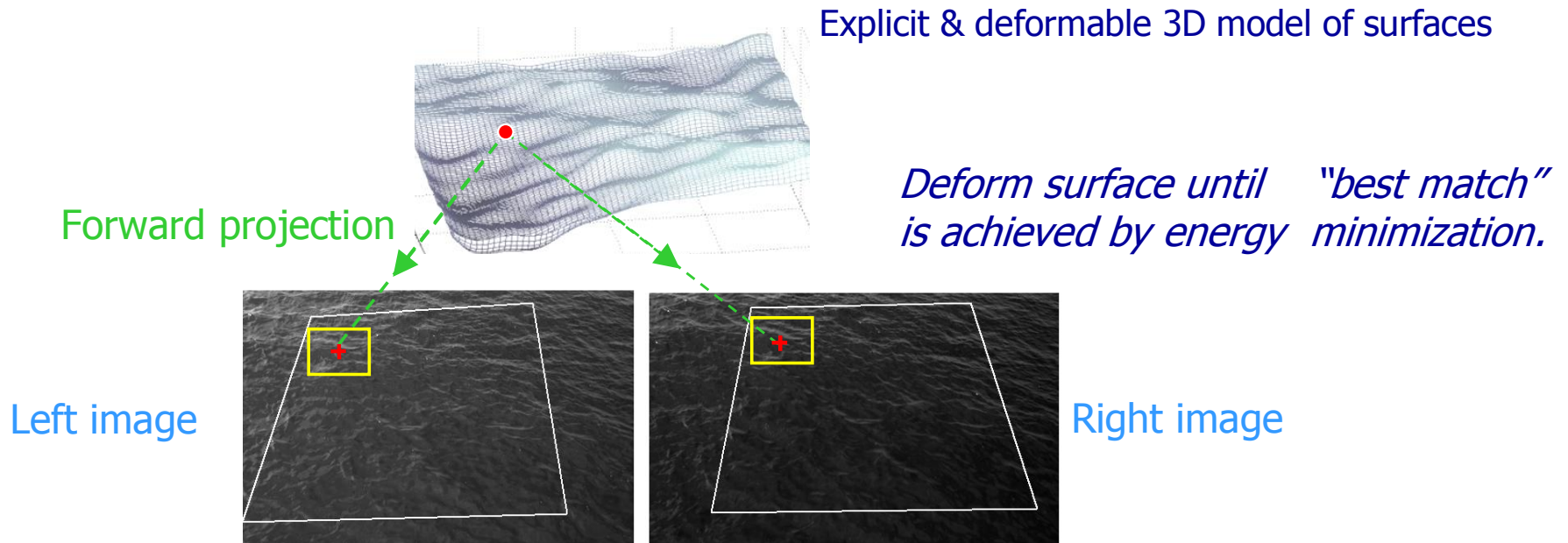


Elevation map after 3 steps



# Elevation method (1 snapshot)

Strategy: adjust a 3D model to the 3D world represented by the data (images) so that an energy functional is minimized.



# Elevation method (1 snapshot)

Graph representation:  $S(u, v) = (u, v, Z(u, v))$

Design a **cost functional** to be minimized:

- Joint estimation of height  $Z(u, v)$  or the waves and its radiance  $f(u, v)$

**Cost:**  $E(S, f) = E_{\text{data}}(S, f) + \alpha E_{\text{geom}}(S) + \beta E_{\text{rad}}(f), \quad \alpha, \beta > 0.$

**Data fidelity term:**  $E_{\text{data}} = \sum_{i=1}^{N_c} E_i$       **where**  $E_i = \int_{\Omega_i} \phi_i \, d\mathbf{x}_i, \quad \phi_i = \frac{1}{2} (I_i(\mathbf{x}_i) - f(\mathbf{x}_i))^2.$

**Regularizers:** penalize the norm of the gradients of the height and the radiance

**Cost as a function of height and radiance**

$$E(Z, f) = \int_U L(Z, Z_u, Z_v, f, f_u, f_v, u, v) \, d\mathbf{u}. \quad \longrightarrow \quad \text{Euler-Lagrange equations}$$



# Elevation method (1 snapshot)

## Necessary optimality conditions:

System of coupled PDEs in height  $Z$  and radiance  $f$  of the surface.

$$\left. \begin{aligned} g(Z, f) - \alpha \Delta Z &= 0 && \text{in } U, \\ b(Z, f) + \alpha \frac{\partial Z}{\partial \nu} &= 0 && \text{on } \partial U, \\ - \sum_{i=1}^{N_c} (I_i - f) J_i(Z) - \beta \Delta f &= 0 && \text{in } U, \\ \beta \frac{\partial f}{\partial \nu} &= 0 && \text{on } \partial U, \end{aligned} \right\}$$

Non-linear term (due to data-fidelity cost):

$$g(Z, f) = \underset{\substack{\uparrow \\ \text{Radiance deriv}}}{\nabla f} \cdot \sum_{i=1}^{N_c} \underset{\substack{\uparrow \\ \text{Photometric error}}}{|M^i| \tilde{Z}_i^{-3} (I_i - f)} \underset{\substack{\downarrow \\ \text{Optical ray and Unit Normal}}}{(u - C_i^1, v - C_i^2)},$$

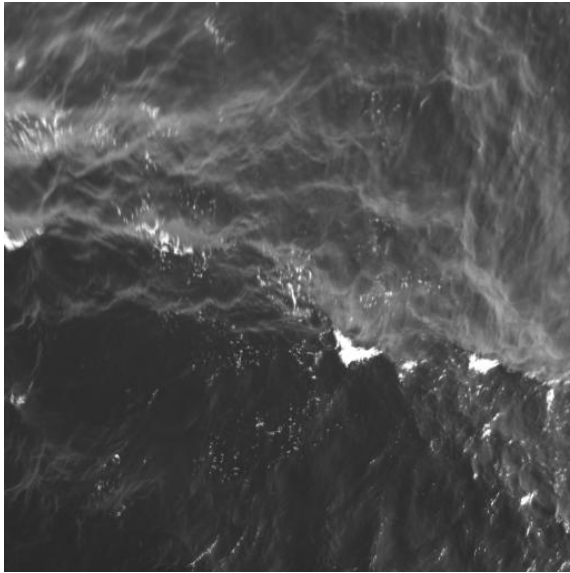
Focal length
Depth of point
Optical ray and Unit Normal

**Multigrid solver:** standard method for non-linear elliptic boundary value problems like this one.

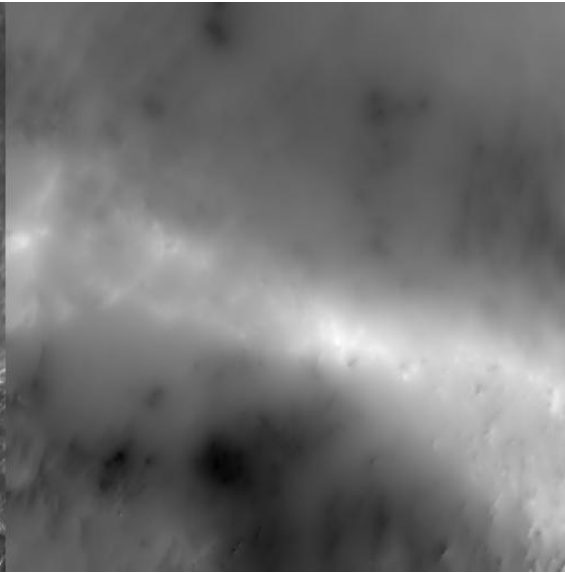
**Steepest descent method** for the system of non-linear PDEs.

# Elevation method (1 snapshot)

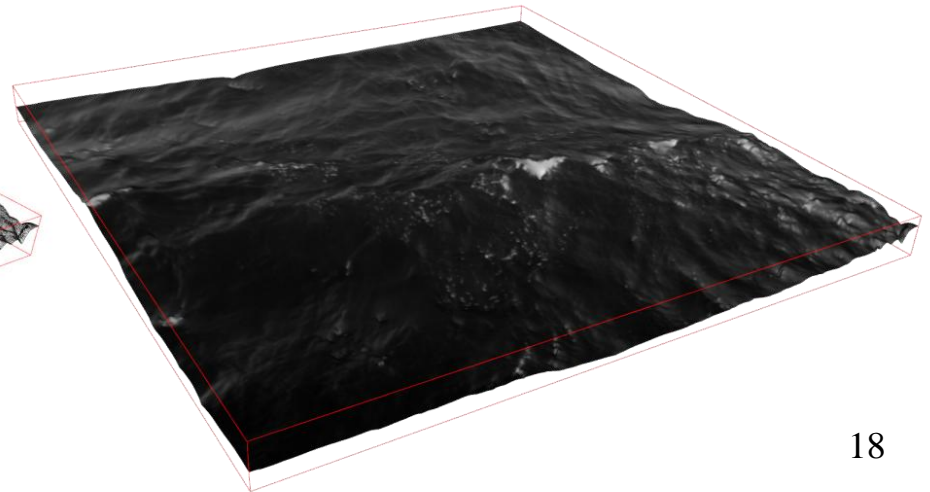
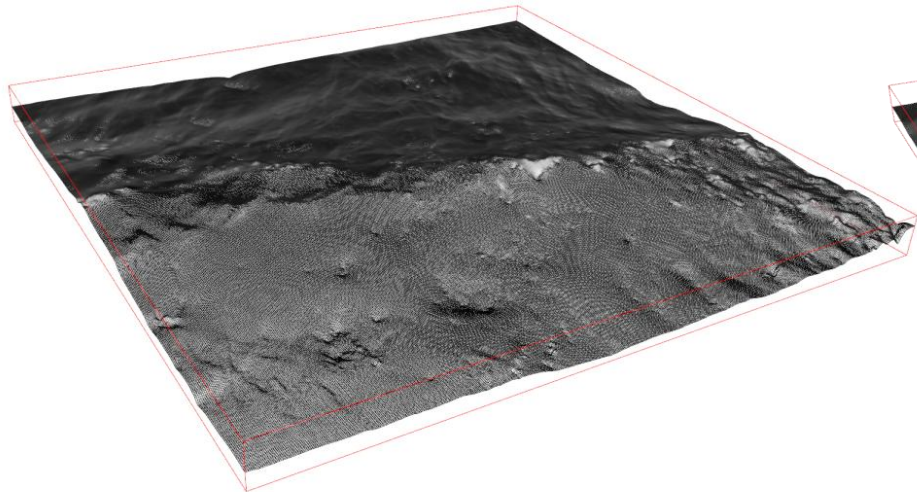
Radiance **f**



Height **Z**

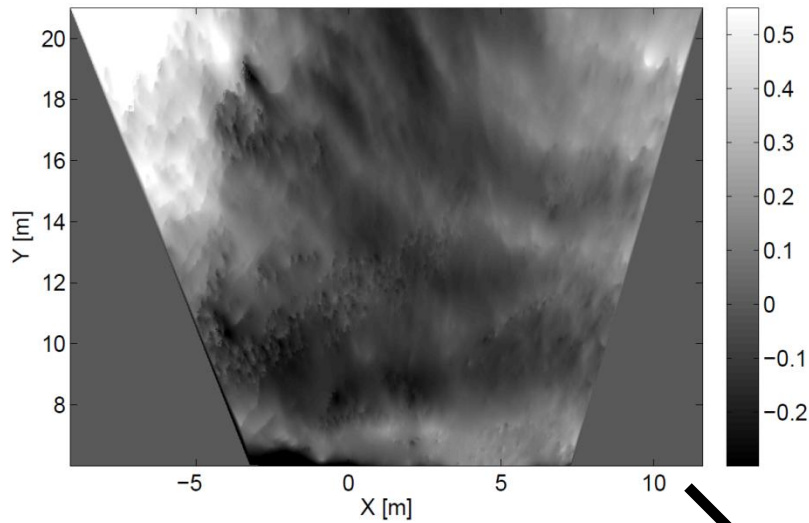


Reconstructed surface & texture (height **Z** and radiance **f**)

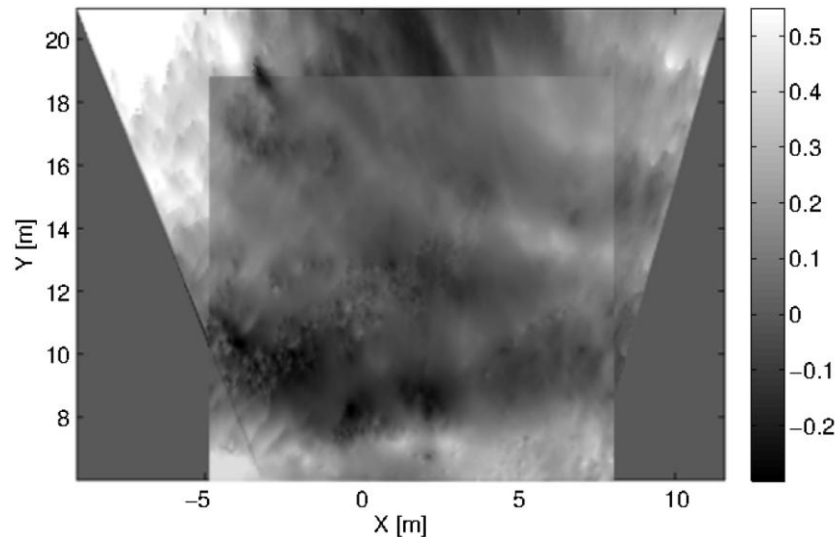
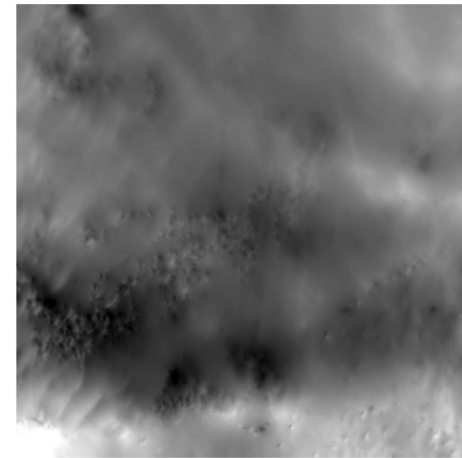


# Comparison of estimated wave heights

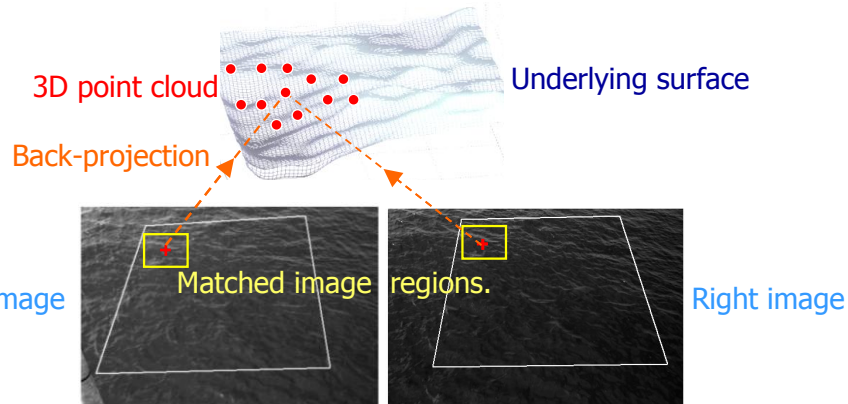
## Disparity method



## Elevation method



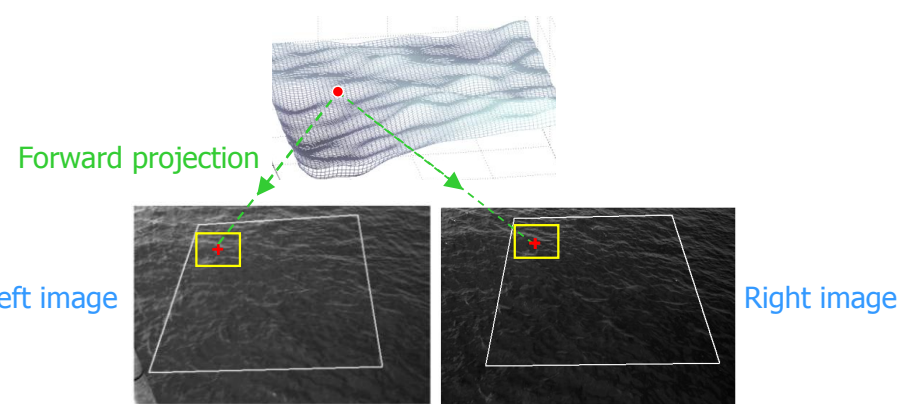
## Disparity method



### ➤ Differences:

- Bottom-up approach: from pixels to surface
- Handle >2 images by pairs
- Requires triangulation + surface fitting.
- Does not take into account scene depth
- Does not take into account surface normal
- No radiance model: sensitive to noise
- Familiar, step-by-step.
- Single PDE in the unknown

## Elevation method



### ➤ Differences:

- Top-bottom approach: from surface to pixels
- Easily handle more than 2 images
- No need to fit a surface through 3-D points
- Takes into account scene depth.
- Takes into account surface normal.
- Radiance model: less sensitive to noise
- Can incorporate physics of the waves.
- More mathematically involved: system of coupled PDEs.



# Things we can do & things we are working on

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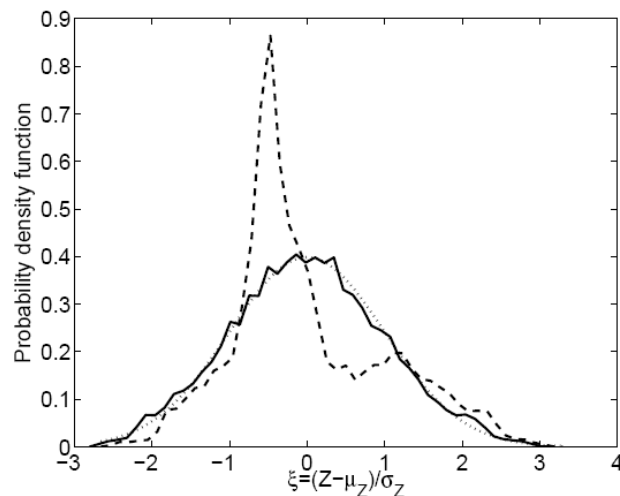
- Enforce wave statistics during estimation.
- Simultaneous snapshot reconstruction.
- Refinement of (varying) camera parameters.
- Better wave analysis.
- Scalable and efficient estimation of wave heights:  
multiresolution + hardware parallelization.

# Enforce wave statistics during estimation

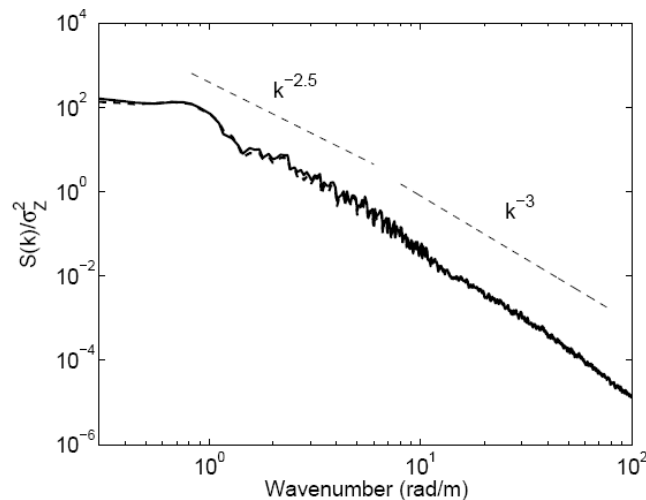
Add a cost penalty to measure statistical wave height distribution error:

$$E_{\text{stat}} := \int_{-\infty}^{\infty} w(z) \frac{1}{2} \left( G(z) - \text{cdf}^Z(z) \right)^2 dz$$

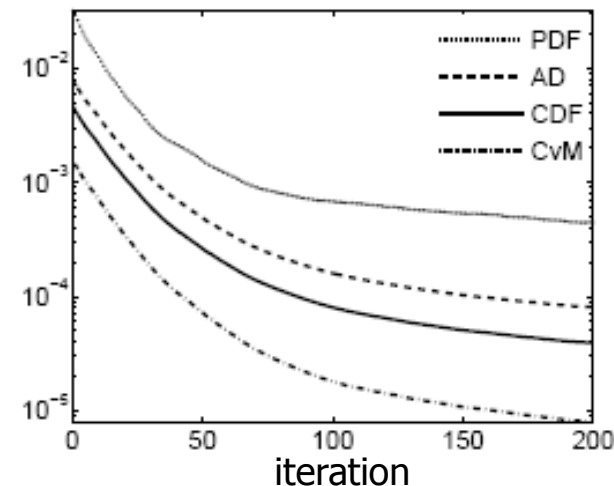
PDFs



Omnidir spectrum



Cost evolution



# Simultaneous snapshot reconstr. Time coherence

**Data fidelity:** measure photo-consistency throughout the video for a candidate surface.

**Regularizers:** enforce **spatial** and **temporal** smoothness of the solution (disparity or height & radiance).

## Disparity method

$$E'_{\text{data}}(\lambda) = \int_T \int_{\Omega} \frac{1}{2} (I_1(\mathbf{x}_1) - I_2(\mathbf{x}_2))^2 d\mathbf{x}_1 dt,$$

$$E_{\text{smooth}}(\lambda) = \int_T \int_{\Omega} \frac{1}{2} \|\nabla \lambda\|^2 d\mathbf{x}_1 dt,$$

## Elevation method

$$E_i(Z, f) = \int_T \int_{\Omega_i} \phi_i d\mathbf{x}_i dt,$$

$$E_{\text{geom}}(Z) = \int_T \int_U \frac{1}{2} \|\nabla Z\|^2 d\mathbf{u} dt,$$

$$E_{\text{rad}}(f) = \int_T \int_U \frac{1}{2} \|\nabla f\|^2 d\mathbf{u} dt,$$

## **Minimization approach:**

- Obtain modified Euler-Lagrange eqs  $\rightarrow$  set gradient descent eqs.
- Discretize and solve using 3-D multigrid methods.

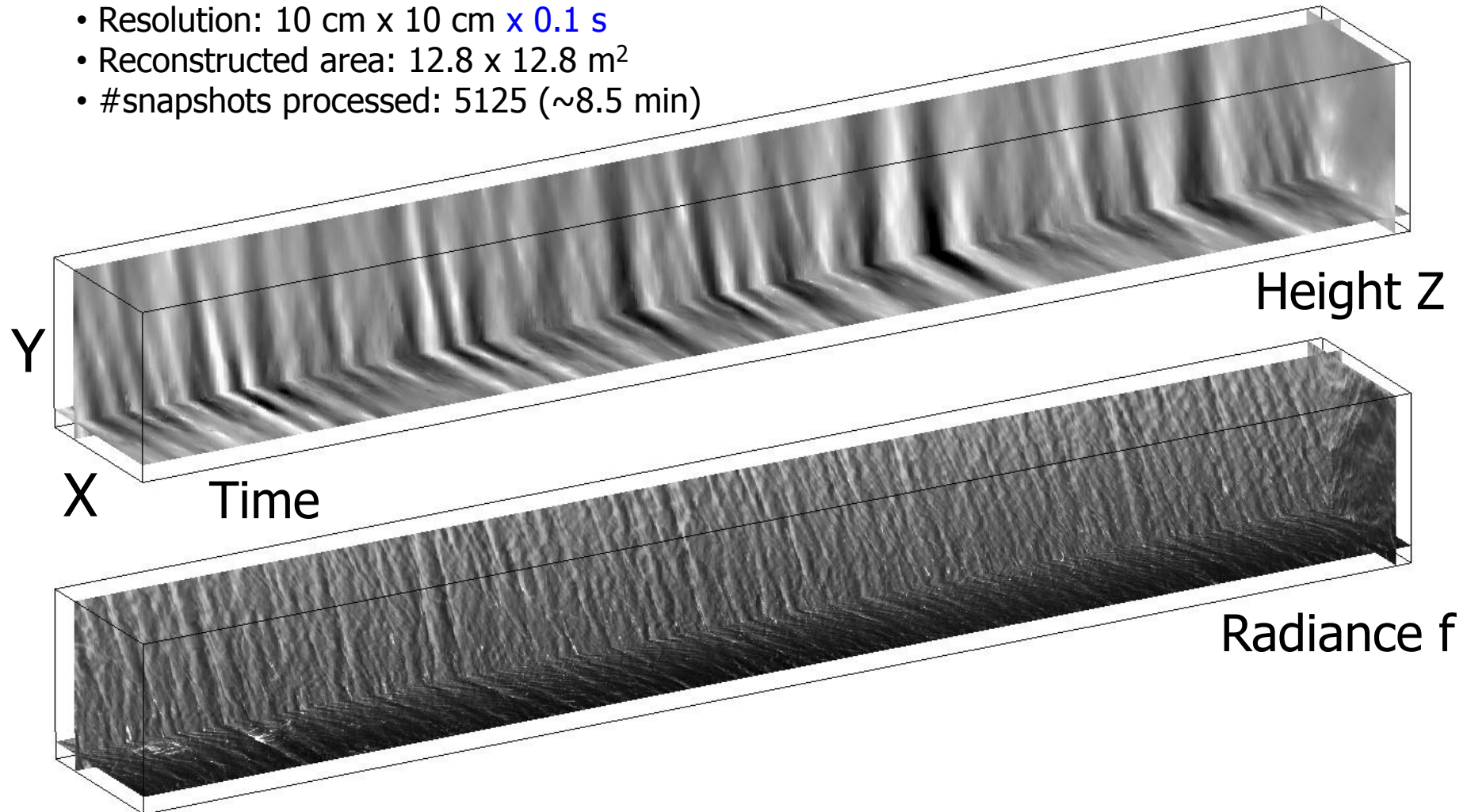
# Elevation method. Estimated wave height volume

Input stereo video (2 cameras) at Crimean Platform:

- Input (subsampling) images: 406 x 309 pixels at 10 Hz frame rate.

Reconstruction:

- Computational grid: 129 x 129 x 1025 points
- Resolution: 10 cm x 10 cm x 0.1 s
- Reconstructed area: 12.8 x 12.8 m<sup>2</sup>
- #snapshots processed: 5125 (~8.5 min)





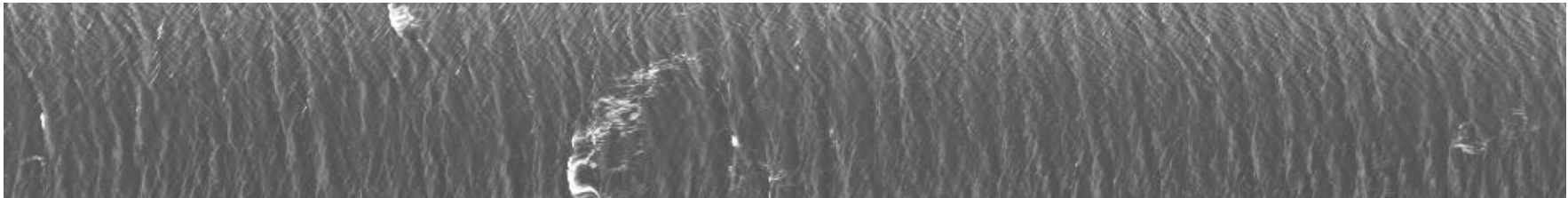
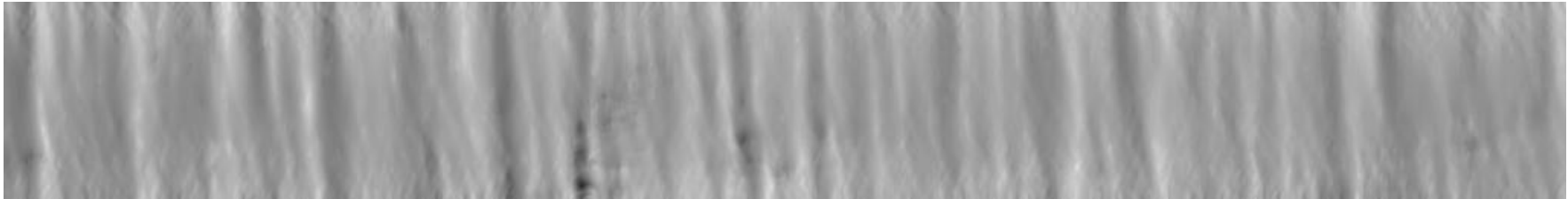
# Elevation method. Estimated wave height volume

Y



Time

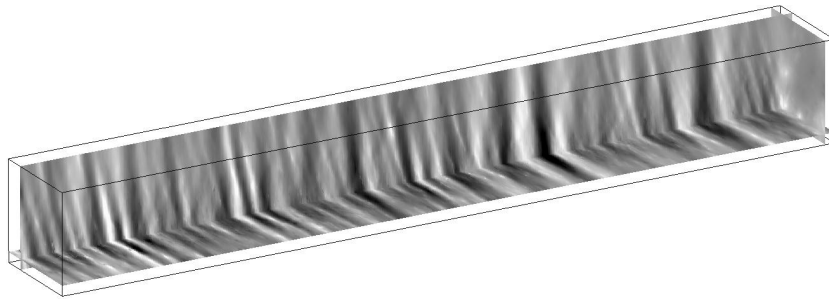
X



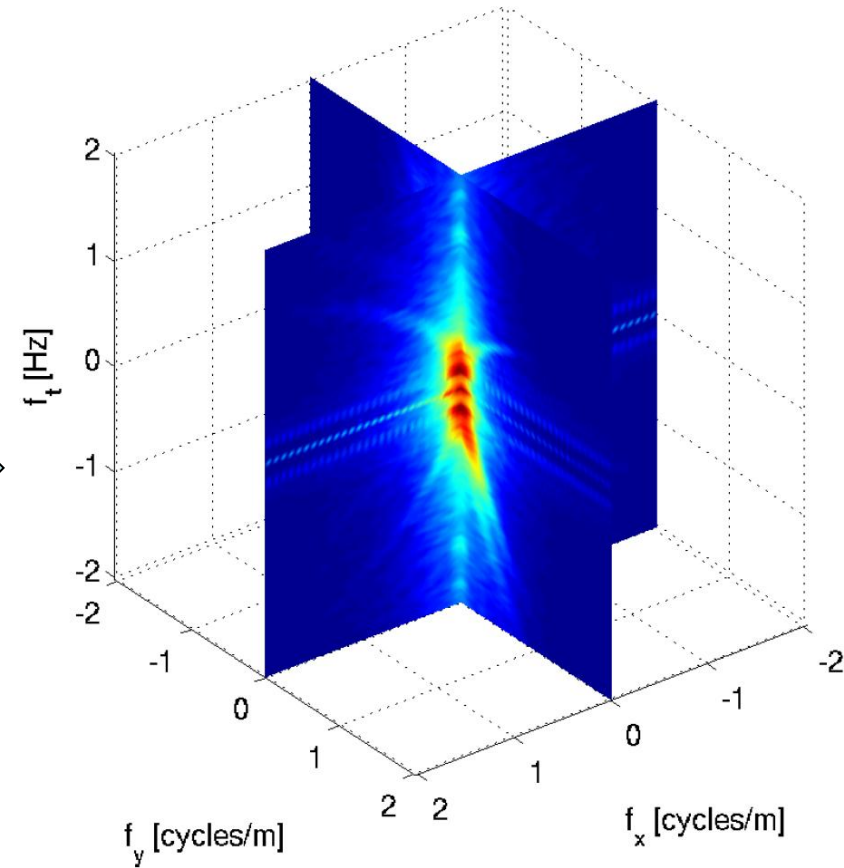
Time

# Estimated 3-D (power) spectrum

Wave height volume  $Z(x,y,t)$



Fourier



Crimea sequence. Input: 129x129x4100.

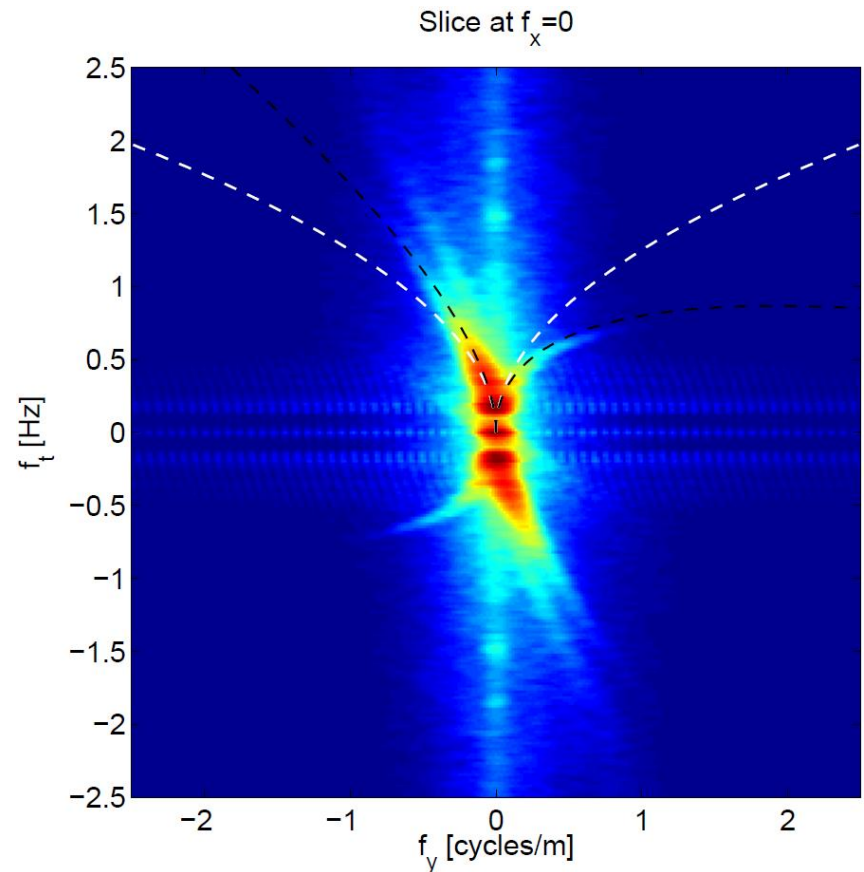
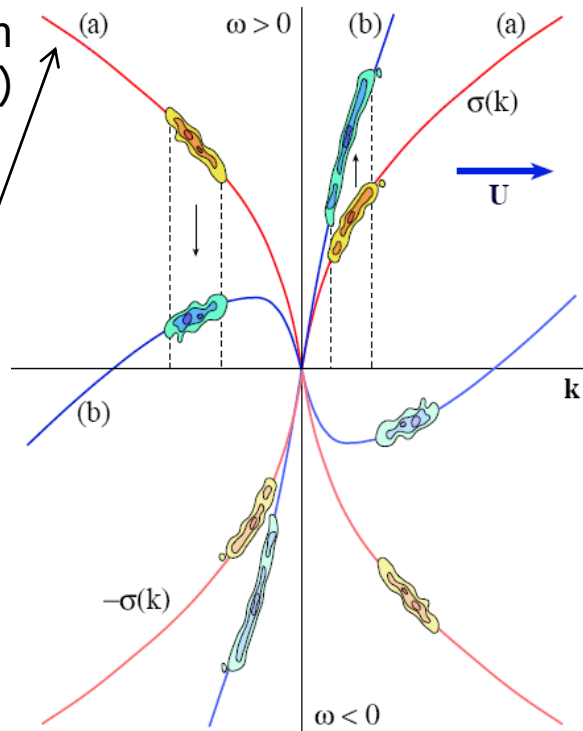
Output: 512x512x512

# 3-D spectrum. Estimation of wave currents

Taking into account the effect of surface currents:

Linear dispersion  
(in deep water)

$$k = \frac{\omega^2}{g}$$

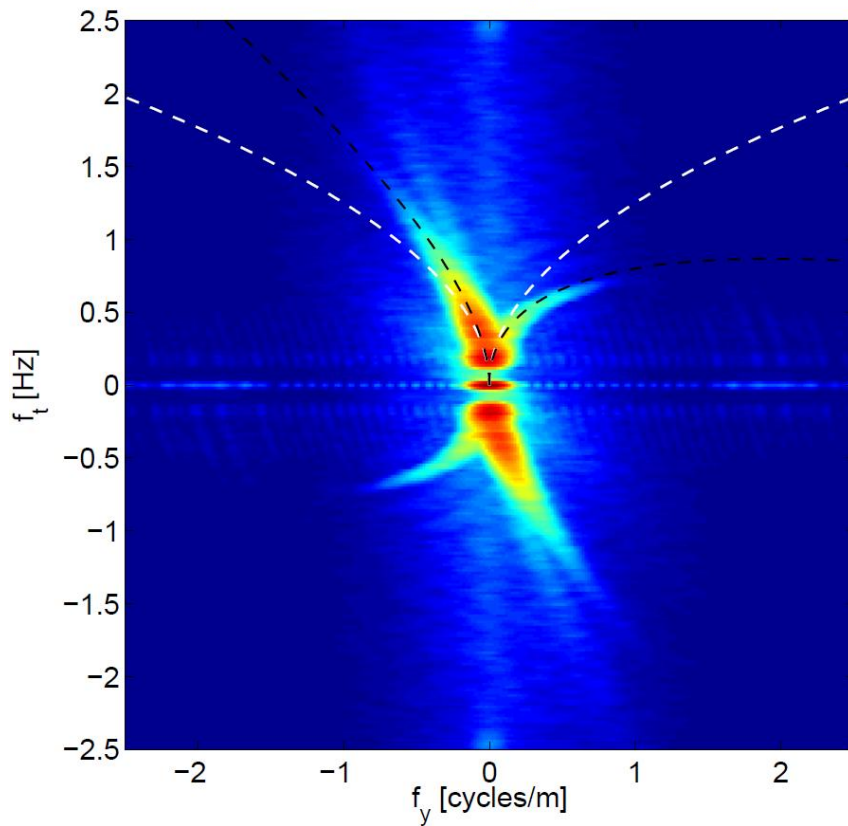


Velocity vector:  $u = (-0.17, -0.45)$  m/s

# Slice of the 3-D spectrum

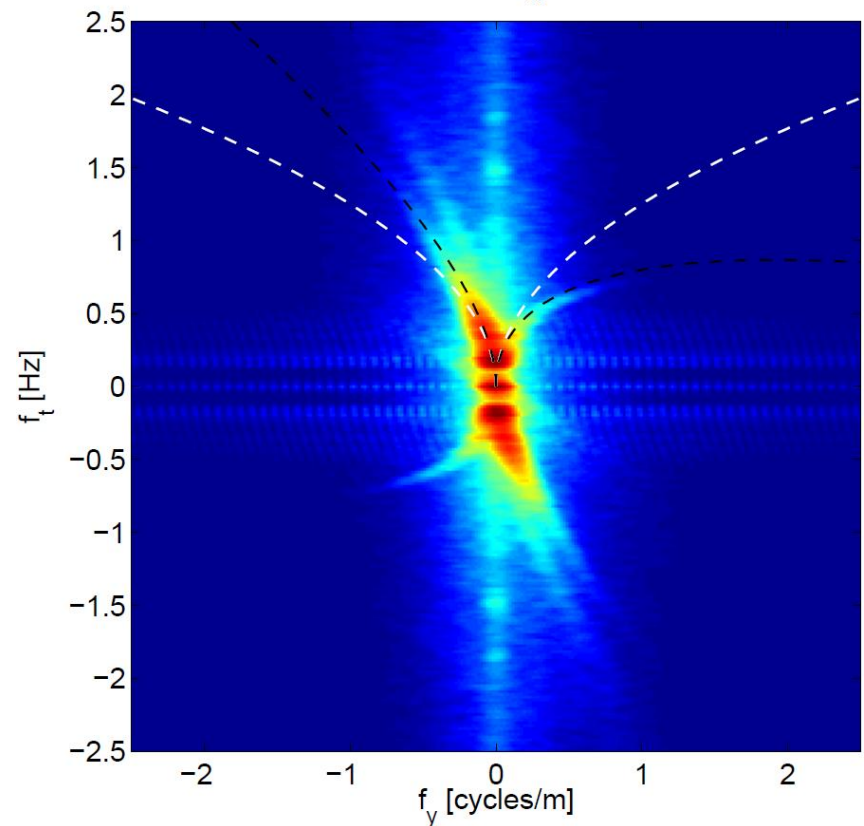
## Disparity method

Slice at  $f_x = 0$

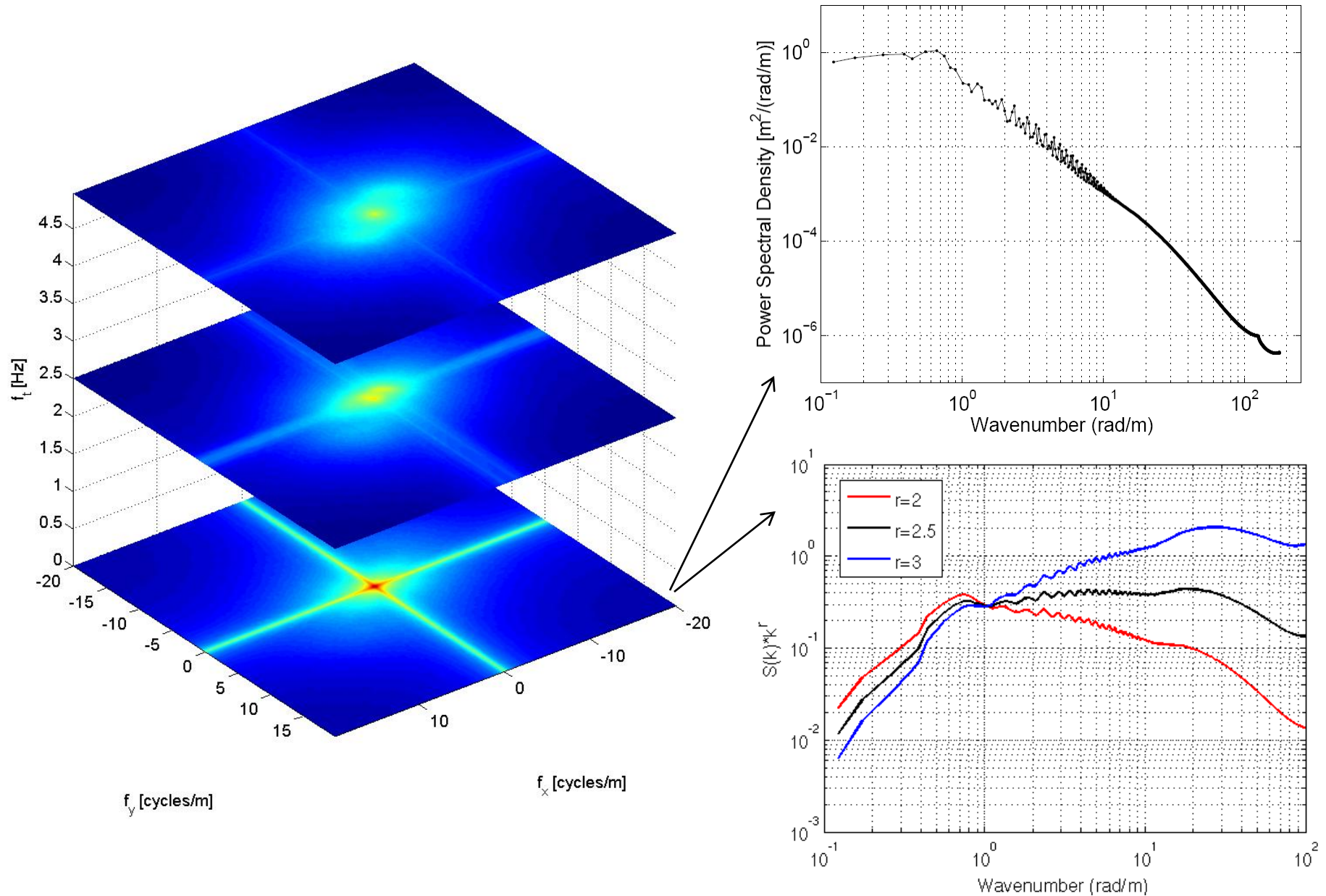


## Elevation method

Slice at  $f_x = 0$



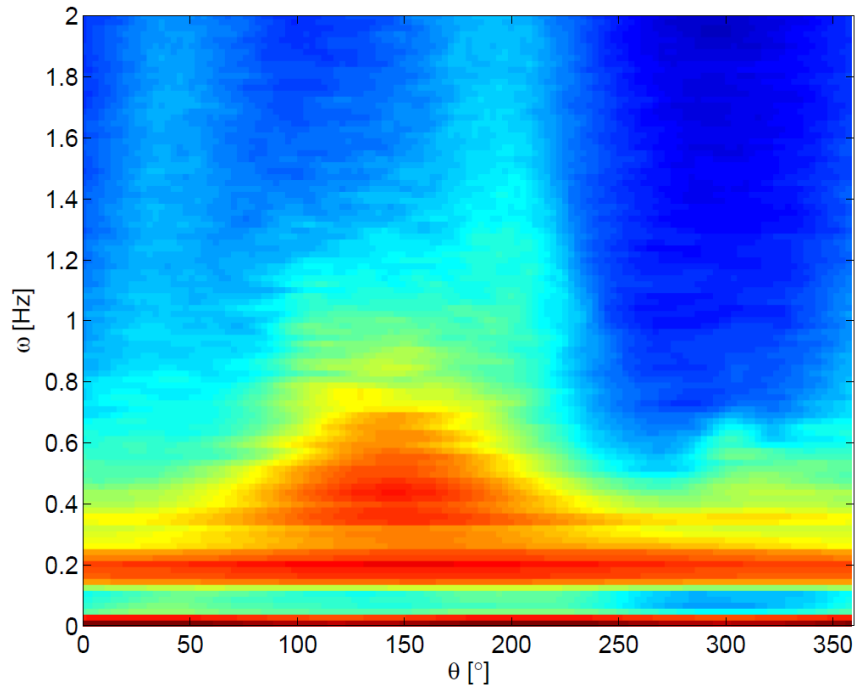
# 3-D spectrum. Omni-directional spectrum



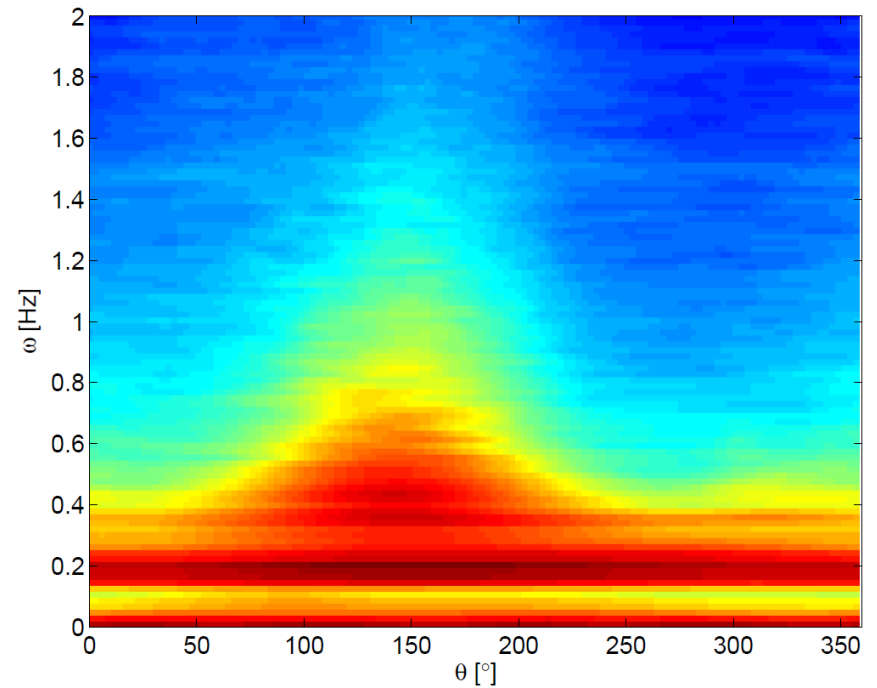


# Directional Spectrum $F(\omega, \theta)$

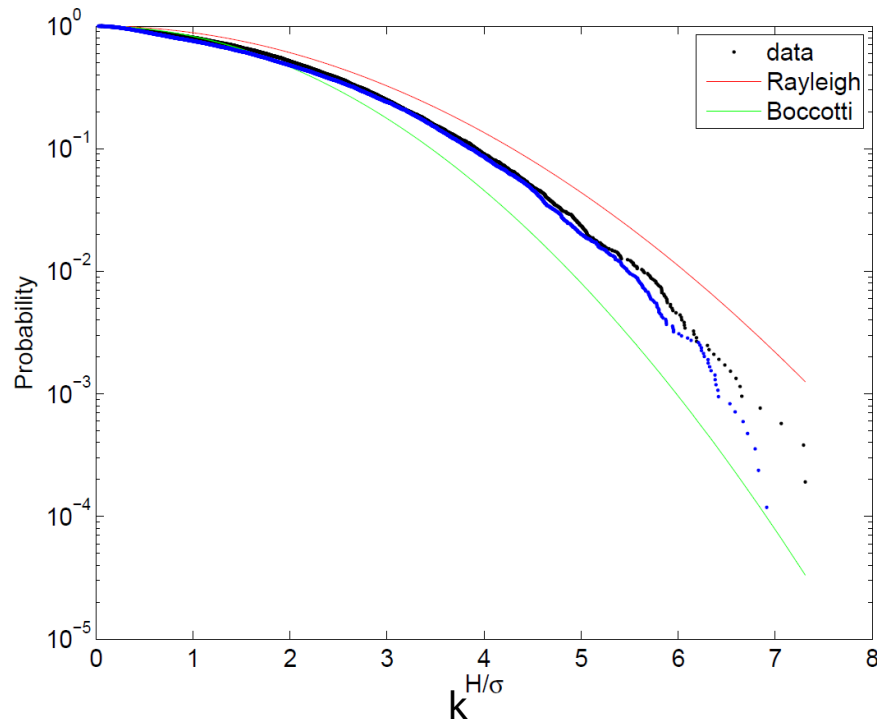
Disparity method



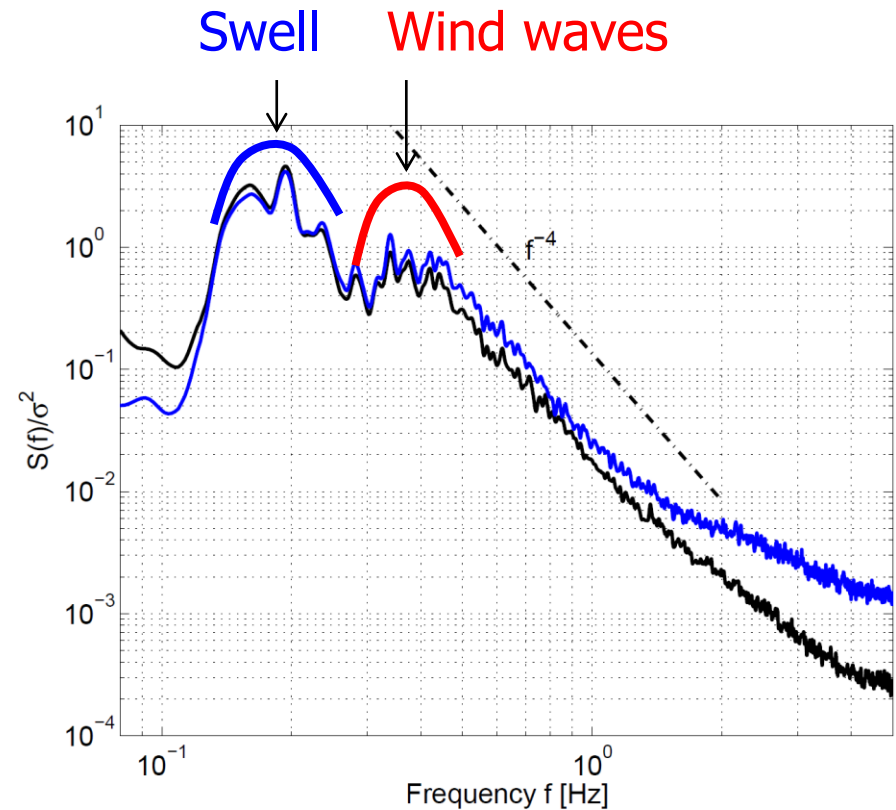
Elevation method



# Analysis of time series at virtual probes.



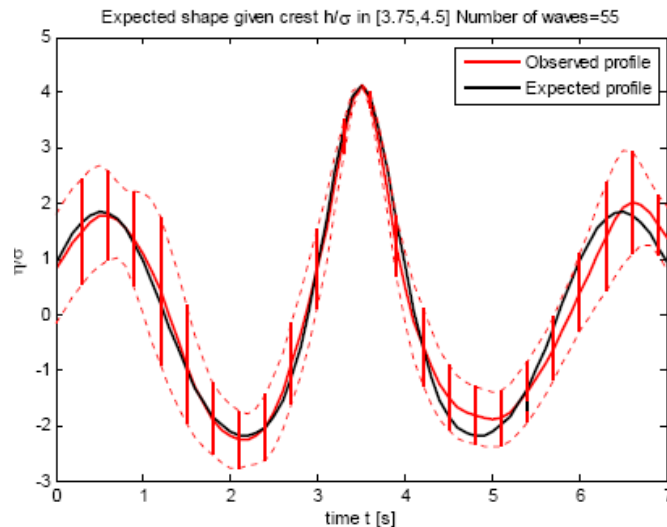
Wave height exceedance probability.  
(disparity method)



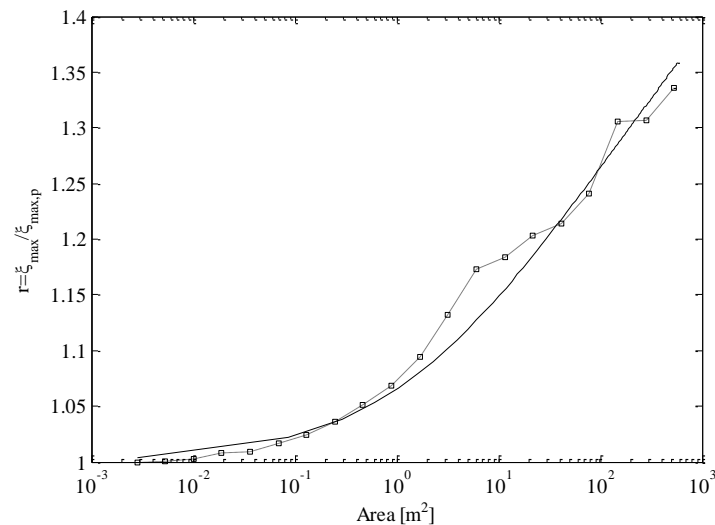
Normalized frequency spectrum.  
disparity method & elevation method

# More Applications

- Comparison of theoretical models with real data using wave measurements:  $H_s$ ,  $T_p$ ,  $T_m$ , etc.
- Statistical analysis: space-time extremes of oceanic states (for the design of offshore structures), etc.



Expected shape of largest waves.



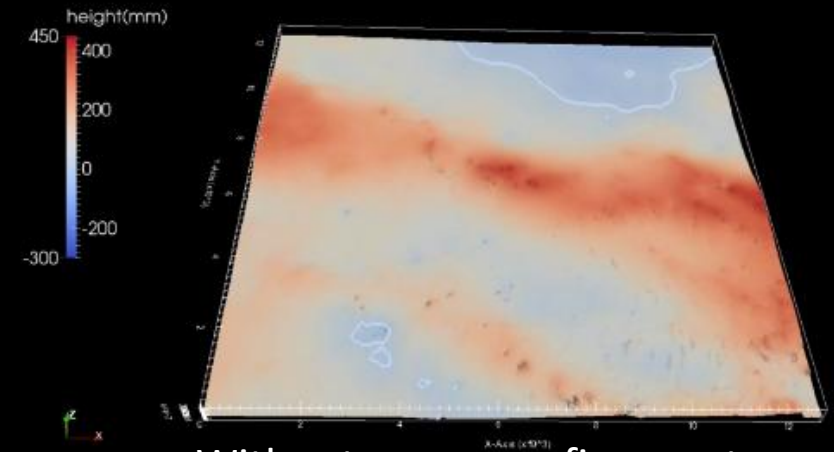
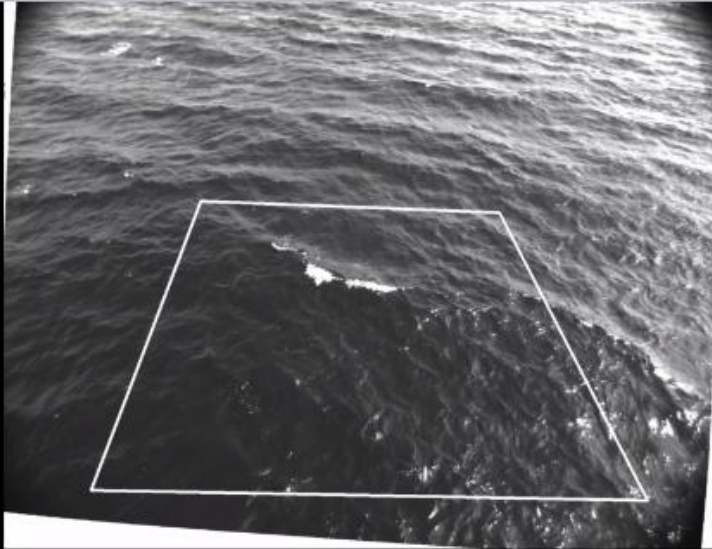
Ratio between the expected maximum wave height over an area and that expected at a point.

# Camera calibration refinement

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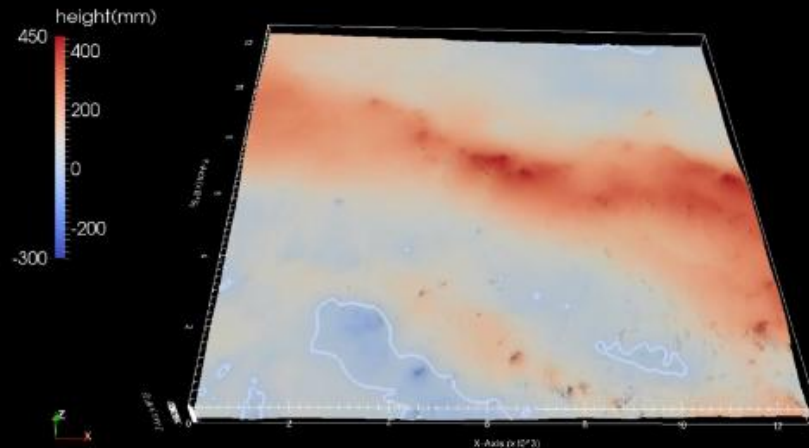
- Camera parameters:
  - Intrinsic: optical components
  - Extrinsic: relative camera pose
- Sources of noise in camera parameters:
  - Manufacturing deviations
  - Manual operation errors
  - Natural factors such as breeze or vibrations
  - Numerical errors during the camera pre-calibration
- Goal: improve robustness of wave measurements with respect to camera perturbations.

# Camera calibration refinement



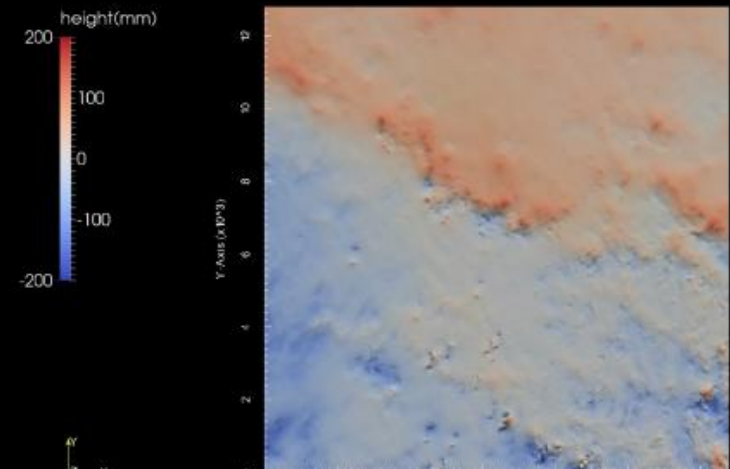
Time: 0.547852

Without camera refinement



Time: 0.547852

With camera refinement



Time: 0.547852

Difference



# Conclusions

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- Stereo reconstruction methods...
  - have more advantages than classical wave measurements (area vs. point measurements).
  - provide reliable statistics and accurate predictions of ocean waves due to the rich information content of video data.
- Advantages of variational methods for wave measurements:
  - Provide dense wave height field estimations.
  - Allow the enforcement of continuity in space & time.
  - Require less post-processing (few assumptions on data).
  - Allow the incorporation of physics of waves.
  - Allow refinement of camera parameters.
- Disadvantages: computational cost (but feasible).
- There are still many related topics to be investigated.

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- ❑ G. Gallego, A. Yezzi, F. Fedele, A. Benetazzo. [Variational stereo imaging of oceanic waves with statistical constraints](#). **IEEE Trans. Image Processing**, 22(11):4211-4223, 2013.
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- ❑ A. Benetazzo, F. Fedele, G. Gallego, P.-C. Shih, A. Yezzi, [Offshore stereo measurements of gravity waves](#), **Coastal Engineering**, 64:127-138, 2012.
- ❑ F. Fedele, G. Gallego, A. Yezzi, A. Benetazzo, L. Cavaleri, M. Sclavo, M. Bastianini. [Euler characteristics of oceanic sea states](#). **Mathematics and Computers in Simulation** 82(6), 1102–1111, 2012.
- ❑ Fedele, F., Benetazzo, A., Forristall, G.Z., 2011. [Space-time waves and spectra in the Northern Adriatic Sea via a Wave Acquisition System](#). **OMAE** 2011.
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- ❑ A. Benetazzo. [Measurements of short water waves using stereo matched image sequences](#). **Coastal Engineering** 53, 1013–1032, 2006.

# Acknowledgements:

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Crimea Data from Dr. Ardhuin.

**THANK YOU FOR YOUR ATTENTION.  
ANY QUESTIONS ?**

More information:

<http://www.gti.ssr.upm.es/~ggb/>

<http://savannah.gatech.edu/people/ffedele/Research/>